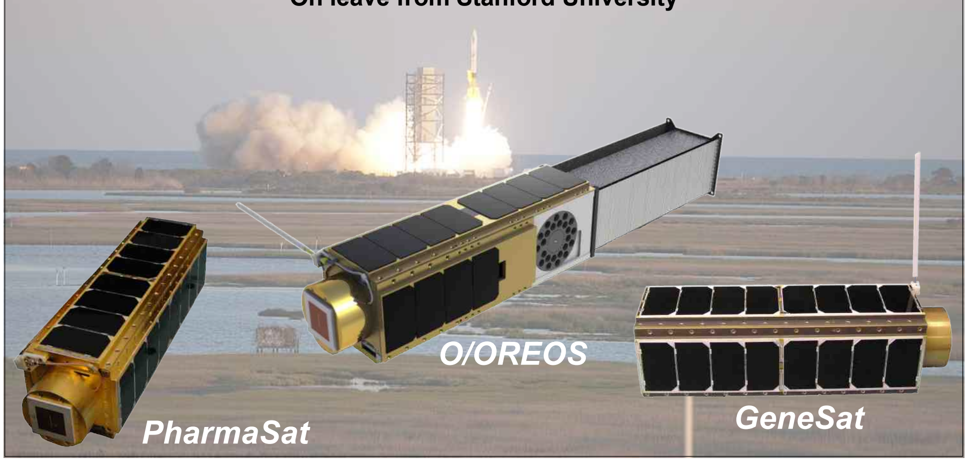
Autonomous Space Science on Small Satellites

Tony Ricco

NASA Ames Research Center, Moffett Field, CA

On leave from Stanford University

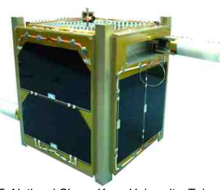


Rationale - Why "SmallSats"?

- **SmallSats are ever more capable:** *Miniature/micro/nano technology* advances
  - fabrication; materials; optics; sensors; actuators; fluidics; MEMS; electronics; communications; instrumentation; data handling & storage
  - *Power* generation & storage density up; power needs down
- **Access to space:** *Low-cost* launch accommodations as secondary payloads
  - military, gov't., commercial; US, Russia, Europe, Canada, India
  - ***Multiple flights possible*** - test, learn, iterate
  - *Low cost* brings new participants: developing nations, universities, high schools
- **Excellent education vehicle:** Significant academic participation worldwide
- **Autonomous operations:** Less reliance on human-tended experiments
  - Eliminates possible bottleneck; can increase reliability
- **Technology migration:** ISS; other "free-flyer" satellite platforms (low Earth orbit, geostationary orbit, libration points); landers/orbiters for moon, Mars, other planets

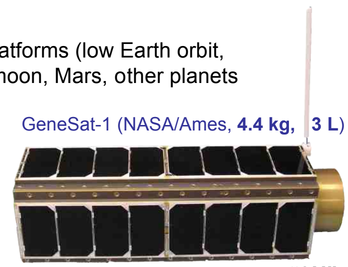
Cal Poly

"1U" CubeSats



PACE: National Cheng Kung University, Taiwan

GeneSat-1 (NASA/Ames, **4.4 kg**, **3 L**)



Launched: Dec. 2006

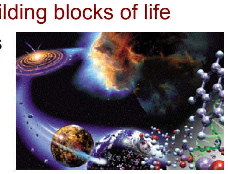
"3U"

Re-entry/disintegration: ~ Aug. 2010

Astrobiology & Space Biology

Astrobiology: origin, evolution, distribution, & future of life in the universe

- Understand details & distribution of prebiotic chemistry -- chemical building blocks of life
- Study potential for life to adapt/survive in extraterrestrial environments
- Search for (signs of) extant or extinct non-terrestrial life
- Find habitable environments in our solar system & beyond
- ***Why: fundamental understanding of life & the universe***

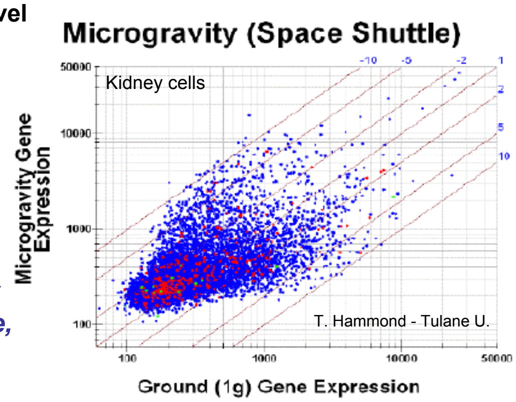


Fundamental Space Biology: effects of the space environment on terrestrial life

- Reduced (micro) gravity effects
  - Mammals: fluid distribution, musculoskeletal loading ⇒ immune stress, bone density decrease, muscle atrophy, slowed wound healing
  - Cells, microorganisms in culture: nutrient and waste transport
- Radiation effects: damage from (high-energy) ionizing radiation
  - Greater outside Earth's magnetosphere, ~70,000 km
  - DNA damage: strand breaks, cell death, mutations
  - Cell membrane, protein, & oxidative damage
- Bio/chemical effects of extraterrestrial environments: lunar dust
- Synergies of combined μgravity & radiation effects possible
- ***Why: human space travel, moon/planetary habitation; insights & therapies for human disease, aging, radiation effects***

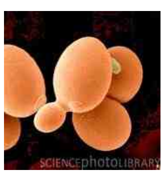
GeneSat: Why Genetics in Space?

- **Current NASA mission is human exploration of the solar system**
  - Must understand adverse effects at the most fundamental levels of biology if therapies (countermeasures) are to be developed
  - *In-situ* experiments produce immediate, more accurate info. (*vs.* sample return)
  - **Modern genetic research is compatible with small, autonomous payloads**
- **Deleterious effects of space travel are relevant to health on Earth**
  - Osteoporosis
  - Muscle atrophy
  - Immune efficiency degradation
  - Radiation damage
  - ***Some biological effects are accelerated in space:*** ***unique insights into their mechanisms are possible, leading to therapies***



Model Organisms

E. coli (GeneSat)
- ~1 x 2 µm bacteria
- nutrient-deprived dormancy (4 – 37 °C) until stable orbit
- GFP fusions to track expression of key genes
- diffuse fluorescence assay of GFP levels
- optical density measurement for population estimate

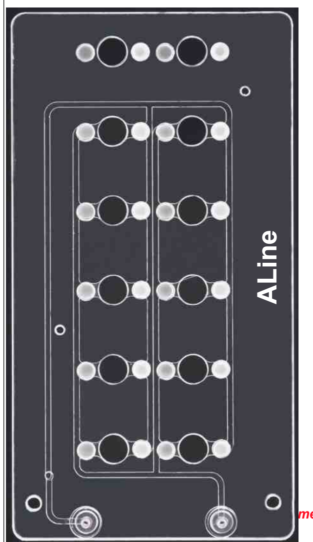


S. cerevisiae (PharmaSat)
- ~ 5 µm fungi, spores
- cold water stasis until stable orbit
- optical density (light scattering) tracks population density
- redox indicator dye tracks metabolic activity

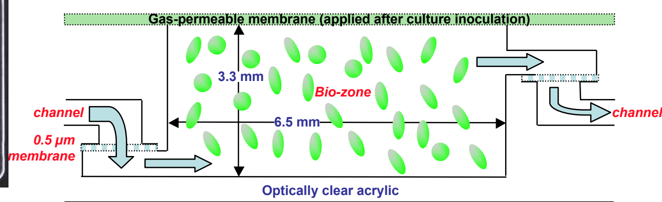

B. Subtilis* & *Halorubrum chaoviatoris (O/OREOS Sat)

C. elegans (µSatellite *in-situ* Technologies Imager)
- mature adults: ~50 µm x 1 mm
- dauer state dormancy (L3) until stable orbit
- green/red fluorescent protein fusions: gene expression
- imaging fluorescence analysis, 2 colors, ~ 9 µm resolution

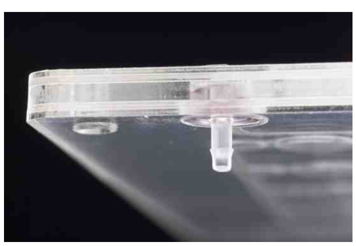
GeneSat Payload System	Date: 11-June-07
Fluidic card	David Oswell, Tony Ricco, Chris Storment, Matthew Piccini, Leanna Levine (Aline)

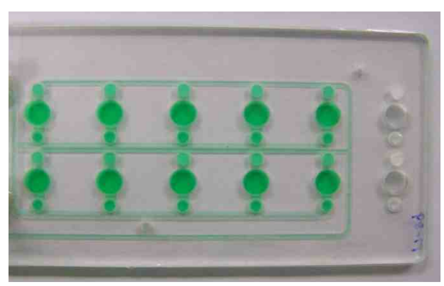


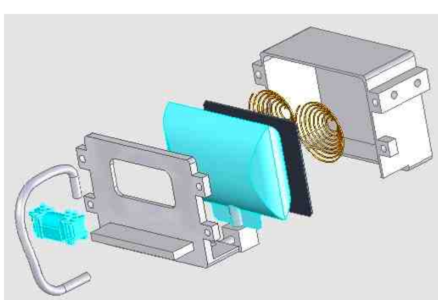
- 12-well culture-and-analysis plate
    - 10 assay wells, 2 control/standard wells
    - 110 µL/well ⇒ 1.1 mL total on-card volume
- Reservoir capacity ~15 mL
- Membrane filter at each well inlet and outlet
- Loaded pre-launch with *E. coli* in stasis medium
- Infused upon stable (**g**, T) orbit with glucose solution to initiate growth

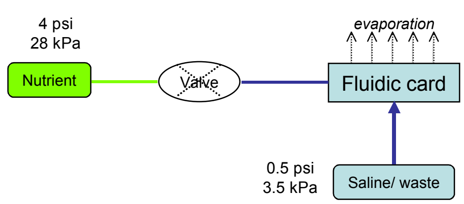


GeneSat Payload System	Date: 11-June-07
Fluidic system	George Swaiss, David Oswell, Chris Storment, Matthew Piccini

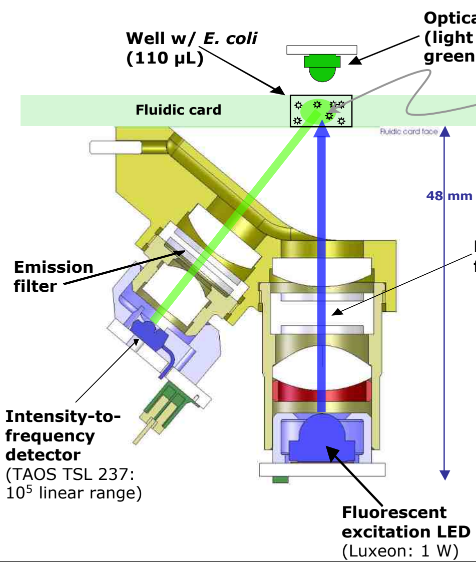


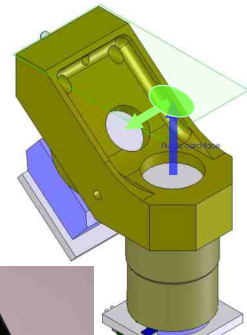






GeneSat Payload System	Date: 11-June-07
Optical system	Linda Timucin, Tony Ricco, Stephane Follonier, Peter Mrdjen, Bob Ricks, Optical Research Associates, Optics One



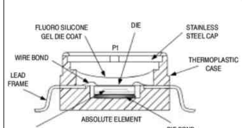


48 X 34 X 18 mm = 29 cm^3 (1.8 in^3)

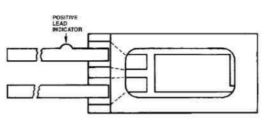
GeneSat Payload System	Date: 11-June-07
Sensors	Chris Storment, Bob Ricks, Matthew Piccini

Pressure Sensor

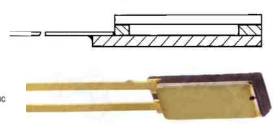
Motorola MPXH6101A



Temperature Sensor



Analog Devices 590

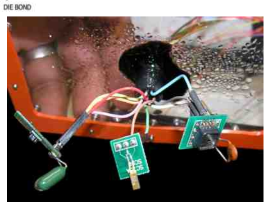


Relative Humidity Sensor

Sensirion SHT15

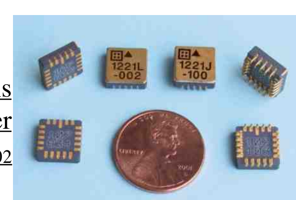
Radiation Sensor (PIN diode)

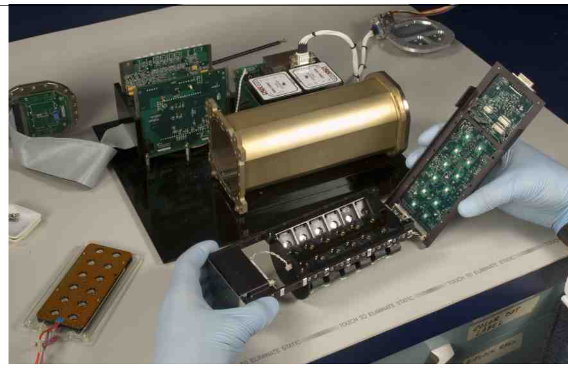
Hamamatsu S3071

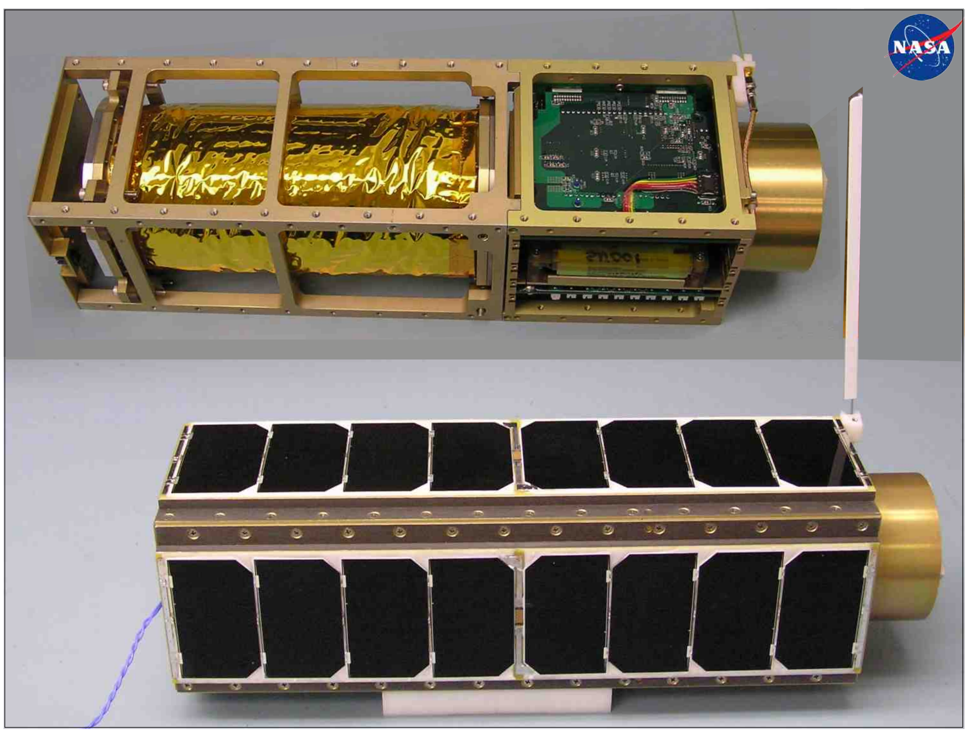


3-Axis Accelerometer

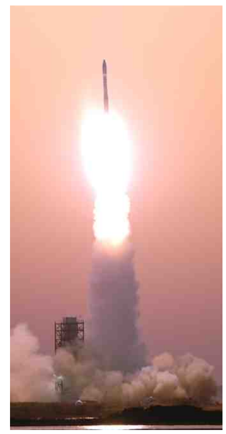
Silicon Designs 1221-002





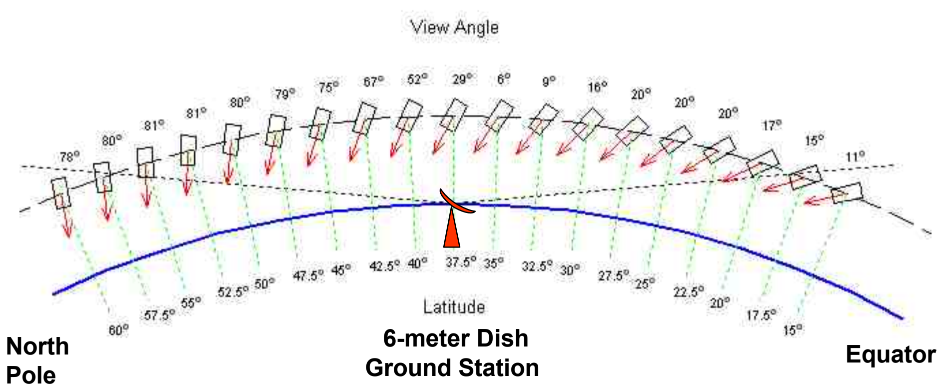


GeneSat Launch: 16 Dec 2006

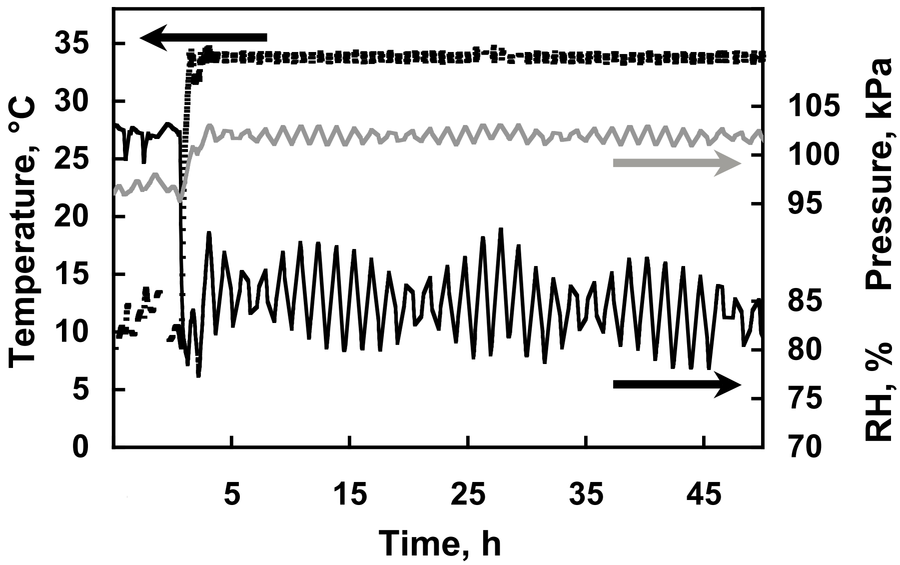


420 km, 90 min orbits; burned up on re-entry, 8-Aug-2010

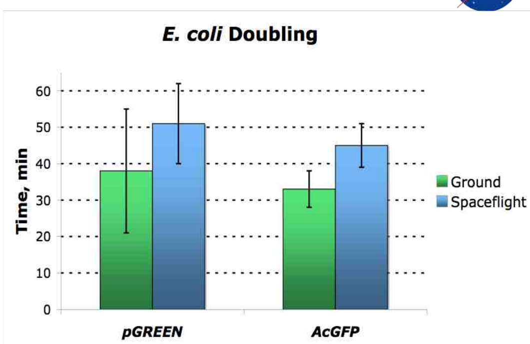
GeneSat Passive Attitude Control Points Patch Antenna Toward SRI Ground Station



GeneSat-1: Results from Low Earth Orbit (~420 km)



DOUBLING TIMES* FOR *E. coli:* FLIGHT vs. GROUND



<u>*Perhaps*</u> there is a systematic difference between flight & ground control, BUT --

- **close to or within estimated uncertainty for both strains**
- **cannot rule out measurement artifacts from the gravity difference:**
  - **bacteria sediment on well bottoms on Earth, not in μ-gravity**
    - – effect on apparent OD, fluorescence need further characterization

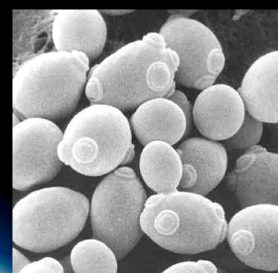
- **<u>Bottom line:</u> growth rates for flight and ground controls are similar**

***using OD data, semi-log plots**

PharmaSat: *Effect of Microgravity on Yeast Susceptibility to Antifungal Drugs*

Tony Ricco, Macarena Parra, John Hines, Mike McGinnis, Dave Niesel, Matthew Piccini, Linda Timucin, C. Friedericks, E. Agasid, C. Beasley, M. Henschke, C. Kitts, A. Kudlicki, E. Luzzi, D. Ly, I. Mas, M. McIntyre, R. Rasay, R. Ricks, K. Ronzano, D. Squires, J. Tucker, B. Yost

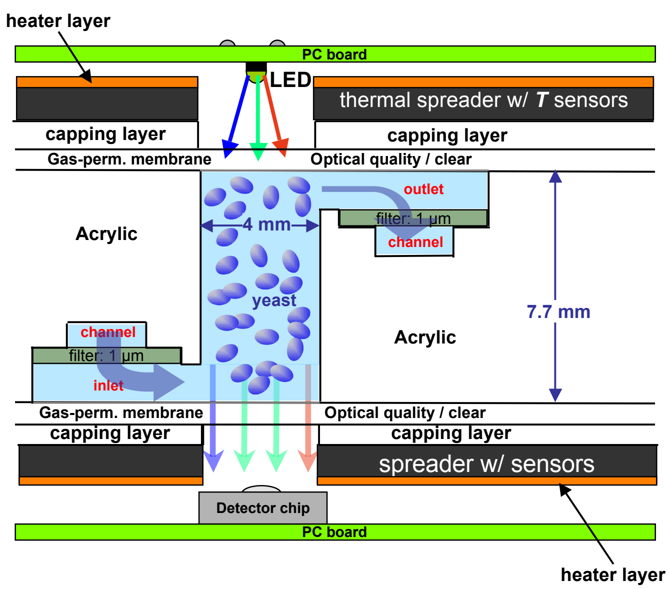
- **Grow yeast cells in multiwell fluidics card in microgravity**
  - Measure efficacy of antifungal agent to inhibit growth of fungus
    - Control + 3 concentrations of antifungal
      - 12 wells each for statistics
- **Measure cell health & growth:**
  - Optical absorbance (turbidity, OD)
  - Viability indicator: Alamar Blue
    - Colorimetric assay: metabolic products cause blue dye → pink dye



S. cerevisiae

LAUNCH: 19 May 2009

Fluidic/Thermal/Optical Architecture

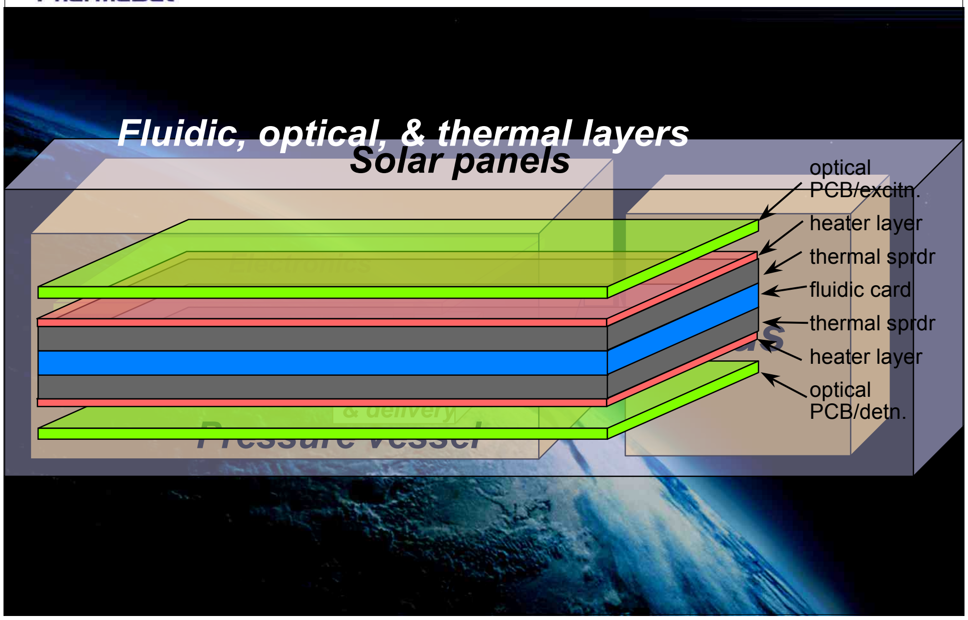


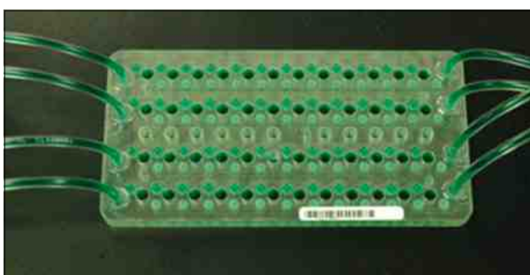
3-color LED for OD & viability: track population during growth, viability using Alamar Blue indicator dye

Fluidic/ optical/ thermal cross-section

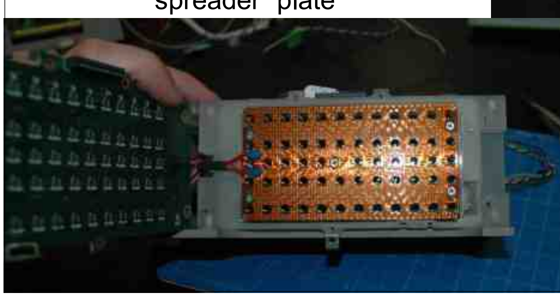
Detector for OD *and* viability measurement using 3-color absorbance

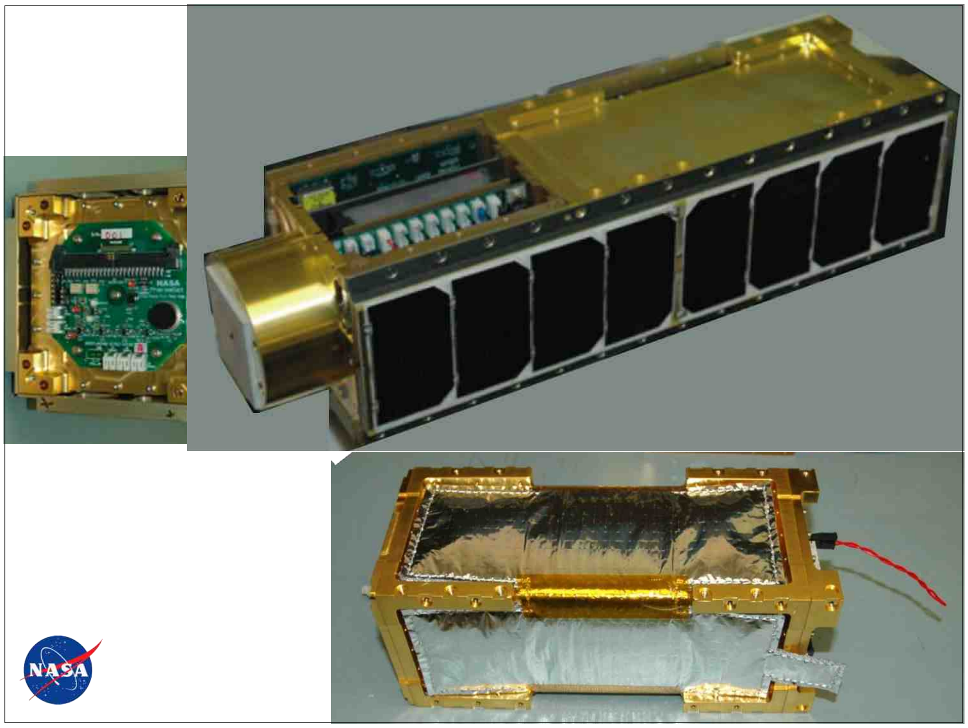
PharmaSat Technology Architecture - 2



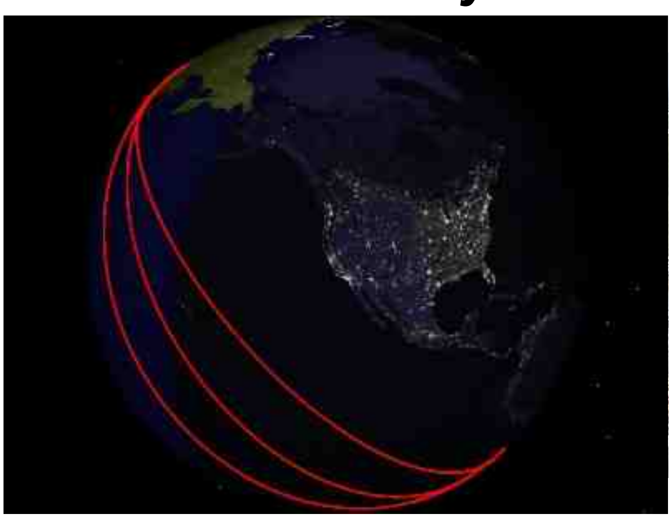


Patterned nichrome-on-kapton heater film with aluminum thermal “spreader” plate





PharmaSat Launch:
19 May 2009

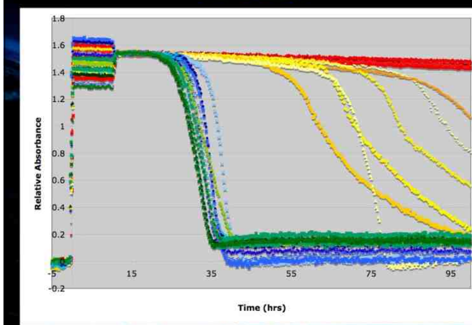


420 km, 90 min orbits; still up there (for a while…)

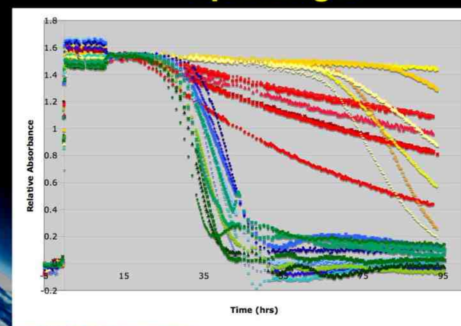
PharmaSat Data (*red channel*)

PharmaSat

Ground



Spaceflight

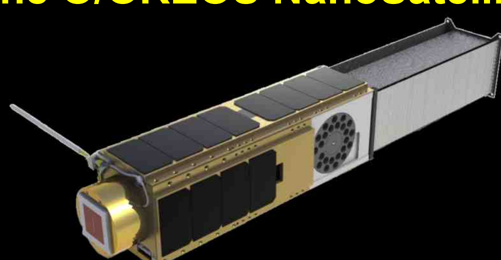


- Hi Antifungal
- MIC* Antifungal
- Lo Antifungal
- Control

**MIC = minimum inhibitory conc.*

- Antifungal effect is clear in both Spaceflight and Ground
- Response for High Antifungal consistent with metabolism being less suppressed in μgravity than on Earth… but cell division remains suppressed

Organism/ORganics Exposure to Orbital Stresses: The O/OREOS NanoSatellite



A. J. Ricco, D. Squires, J. W. Hines, P. Ehrenfreund,[1]
R. Mancinelli[2], A. Mattioda, W. Nicholson[3], R. Quinn[2], O. Santos

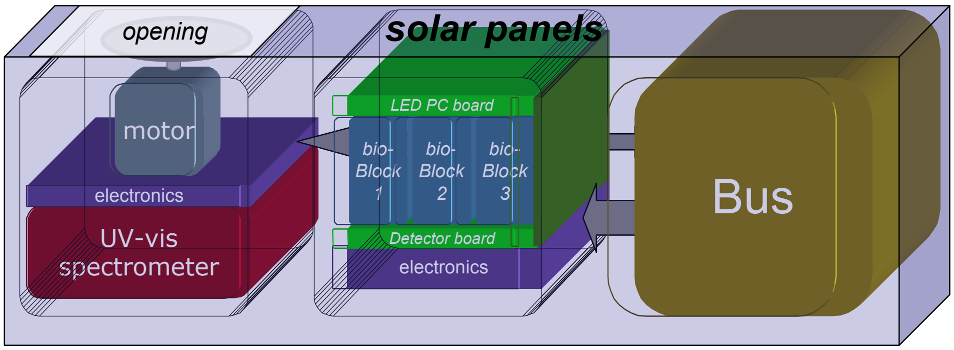
Science support: N. Bramall, J. Chittenden, K. Bryson, A. Cook, M. Parra, D. Ly

Development by the NASA-Ames
Small Spacecraft Payloads & Technologies Team

NASA Ames Research Center
[1] George Washington University
[2] SETI Institute
[3] University of Florida/Kennedy Space Center

O/OREOS Dual-Payload Technology Architecture

*Each P/L experiment-plus-instrument contained in a **single 10-cm cube***

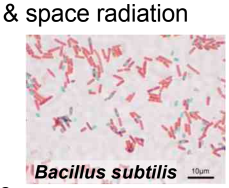


Organics Payload
- **4 organics**
- **4 environments**
- **UV-vis. spectrometer**

Biology Payload
- **2 biological specimens**
- **3 growth initiation times**
- **optical measurements**

Payload 1: **Space Environment Survivability of Live Organisms (SESLO)**

- Two organisms, wildtype & mutant, exposed to µgravity & space radiation
  - < 10^{-3} x Earth gravity
  - 2 – 20 Gy total dose over 6 mo in 650 km orbit
    - 0.1 Gy is galactic cosmic radiation

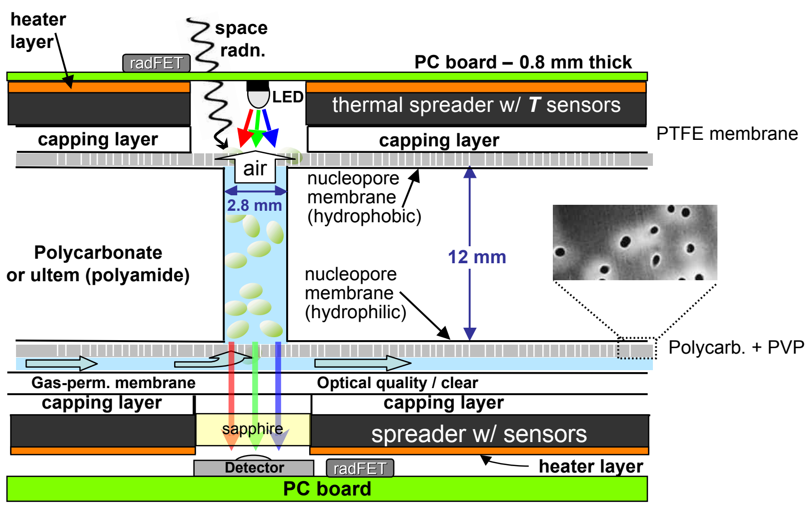


- Dry organisms on µwell walls pre integration
- Rehydrate & feed 6 µwells / organism: *t* = **2 wk**, **3 mo**, **6 mo**

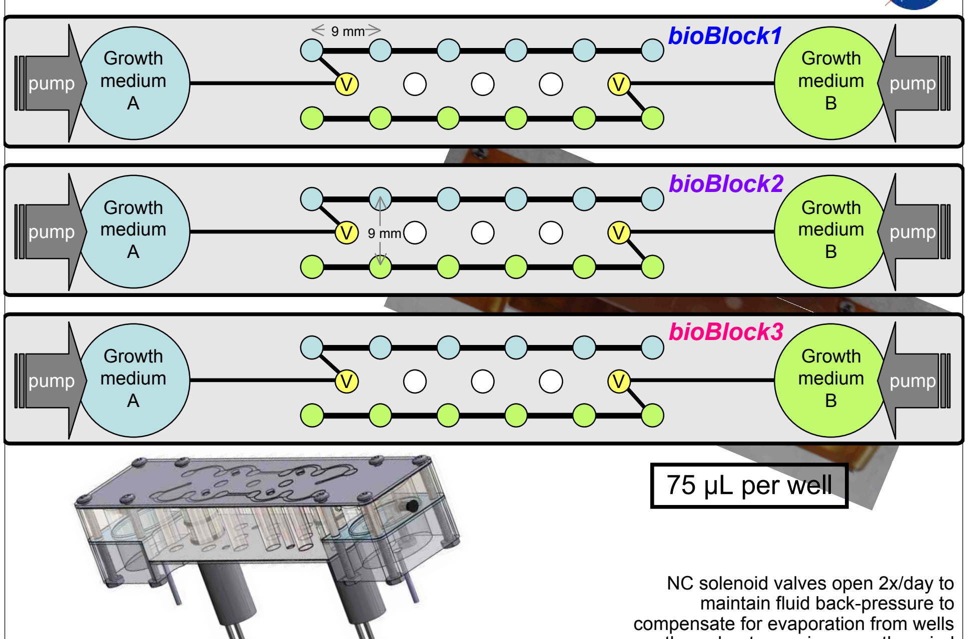
- Grow @ **35 – 37 ± 2 °C for 1 – 17 days**
- Measure RGB transmittance @ **615**, **525**, **470** nm
  - track culture population via calculated optical density (both organisms)
  - track metabolic activity via **Alamar Blue**
- Sensors: ***T***, ***p***, ***RH***, ***rad*** (integrated dose), **µgrav**
  - » temperature (6 sensors per 12-well bioblock)
  - » pressure, relative humidity (1 sensor each)
  - » radiation total dose @ both ends of wells (2 radFETs)
  - » microgravity levels calc'd. from solar panel currents

SESLO (bio) Fluidic/Thermal/Optical Architecture

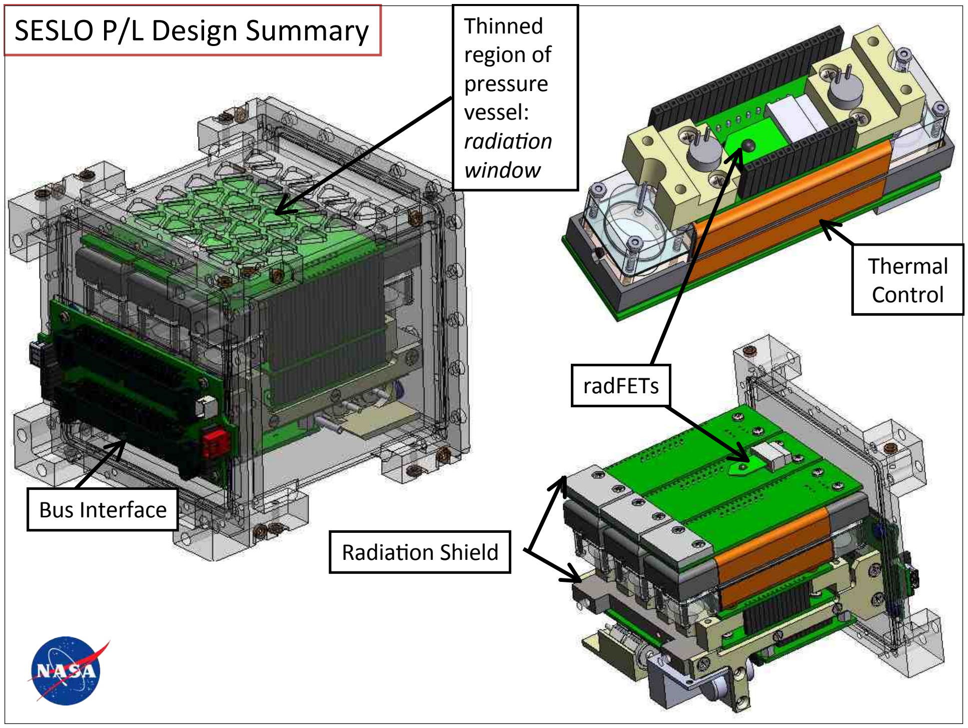
Fluidic / optical / thermal cross-section

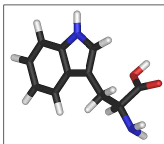


SESLO Integrated Fluidic System: 3 independent bioBlocks

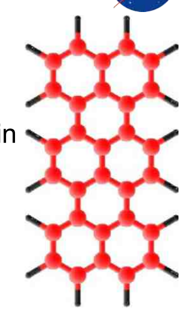


NC solenoid valves open 2x/day to maintain fluid back-pressure to compensate for evaporation from wells throughout organism growth period

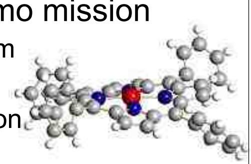




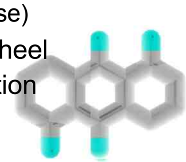
Payload 2: Space Environment Viability of Organics (SEVO)

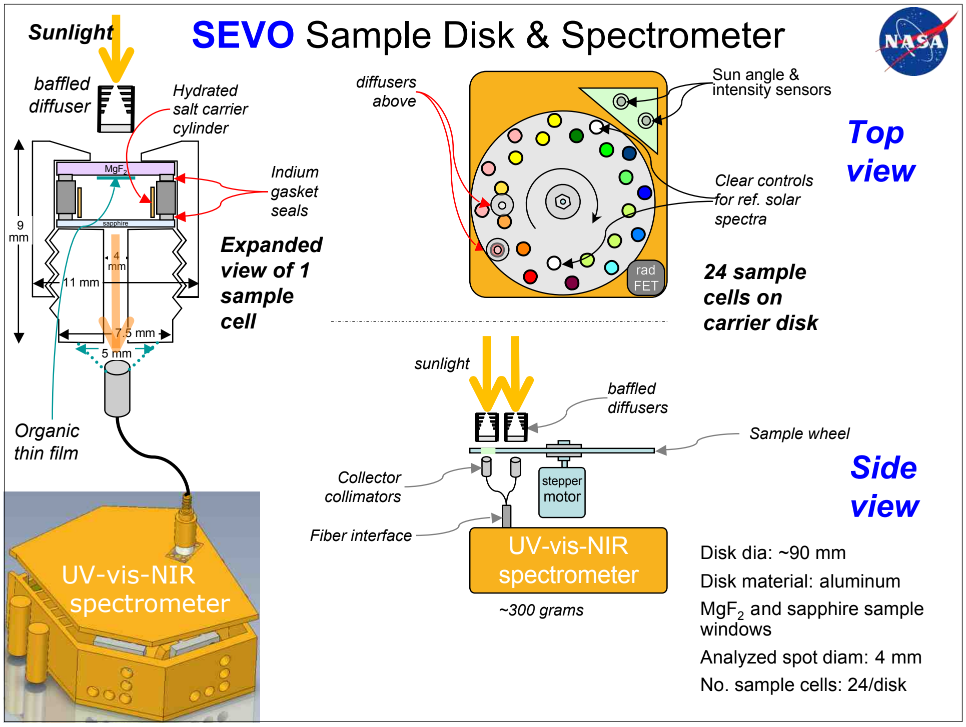


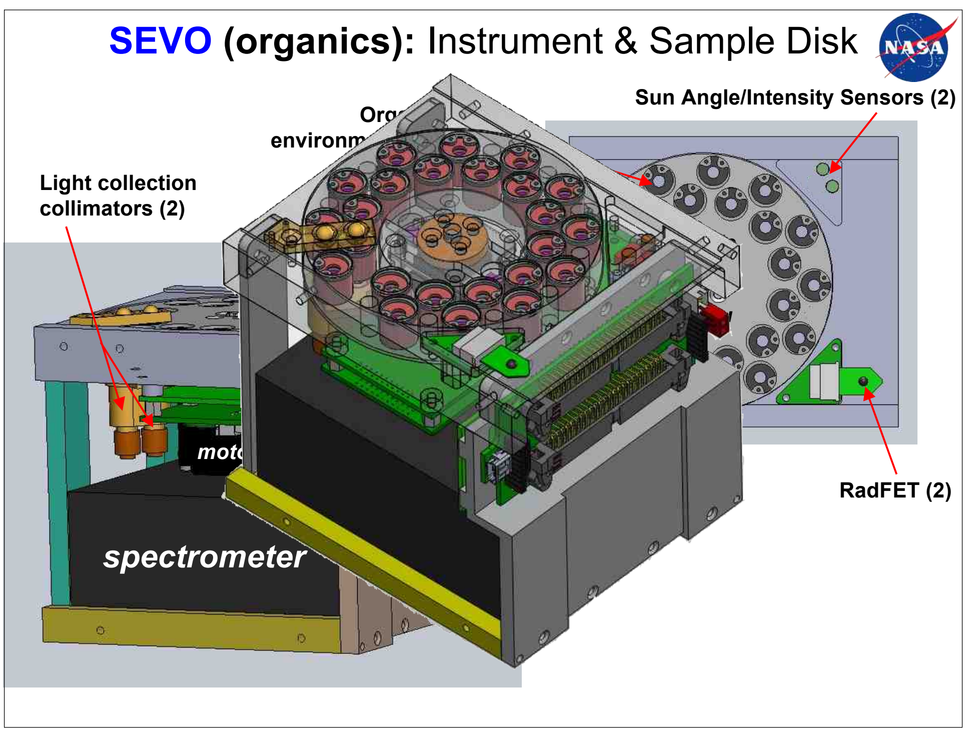
- **6-mo exposure** of organics to space
  - amino acid; polyaromatic hydrocarbon; quinone; porphyrin
  - 4 self-contained sample micro-environments: **interstellar** (vacuum)**, lunar, martian, brine** (humidity only)
  - ionizing radiation: ~ 50 Gy = 5 krad
  - solar exposure 20 – 35% of total time, ~120 - 2500 nm
- Measure **UV-vis-NIR spectrum *daily*** over 6-mo mission
  - for all 18 organic films & 6 references, 200 - 1000 nm
  - sun is light source for spectroscopy
  - solar spectral features: internal wavelength calibration



- Sensors: T_{sample}, T_{spec}, I_{solar}, θ_{solar}, ***rad***(integrated dose)
  - temperature: multiple sensors, spectrometer & sample wheel
  - sun angle: acquire spectra only with appropriate illumination
  - solar intensity: calibration with each sample spectrum
  - radiation total dose: near cells

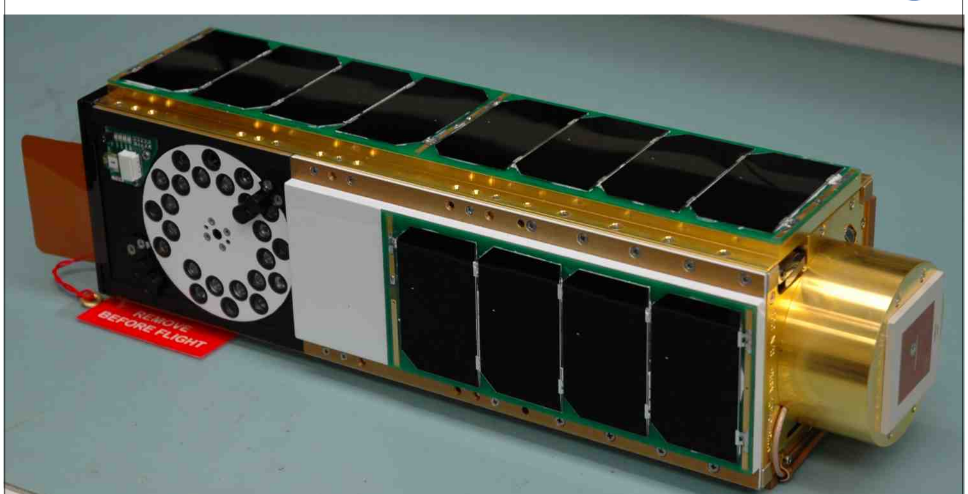



SEVO Sample Disk & Spectrometer
Sunlight
baffled diffuser
Hydrated salt carrier cylinder
MgF_2
sapphire
Indium gasket seals
9 mm
4 mm
11 mm
7.5 mm
5 mm
Expanded view of 1 sample cell
Organic thin film
UV-vis-NIR spectrometer
diffusers above
Sun angle & intensity sensors
Clear controls for ref. solar spectra
rad FET
Top view
24 sample cells on carrier disk
sunlight
baffled diffusers
Sample wheel
Collector collimators
stepper motor
Fiber interface
UV-vis-NIR spectrometer
~300 grams
Side view
Disk dia: ~90 mm
Disk material: aluminum
MgF_2 and sapphire sample windows
Analyzed spot diam: 4 mm
No. sample cells: 24/disk


SEVO (organics): Instrument & Sample Disk
Sun Angle/Intensity Sensors (2)
Light collection collimators (2)
spectrometer
RadFET (2)

O/OREOS Flight Prototype

O/OREOS Nanosatellite



Launch: November 19, 2010 (Kodiak, Alaska)

Conclusions

The tools of bio- and micro-technology combined with automation & integration enable a range of biology experiments in small space platforms

- **Small satellites enable more experiments: space access, low cost**
- **Fundamental biological effects/phenomena explored in a unique environment**
  - Human health & safety
  - Origin, evolution, distribution, & future of life in the universe (astrobiology)
  - Unique zero-shear-rate suspensions of cells & microorganisms
- **Relevance to terrestrial medicine & pharma development**
  - Accelerated test platform: osteoporosis, muscle atrophy, immune impairment, radiation effects
  - Novel conditions impact microorganism function including metabolic processes, secreted proteins
  - Spaceflight environment increases the virulence of some pathogens
  - Growth of ultra-low-defect-density protein crystals